PHYSIOLOGY, BIOCHEMISTRY, and CHEMISTRY associated with MAXIMUM YIELD CORN

A Proceedings of a
Research Roundtable for
Maximum Yield Research
(MYR) of the Future

sponsored by
Foundation for Agronomic
Research (FAR) and

Potash & Phosphate
Institute (PPI)

St. Louis, Missouri
November 11-12, 1985

Seasonal N, P, and K Uptake Rates

Associated With High Yield Corn[1]

by

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ABSTRACT

Effects of improved hybrid potential, increased nutrient application, better water management, and significantly higher plant population on rates and amounts of dry matter and nutrient accumulation by corn (Zea mays L.) yielding more than 10.0 Mg ha^{-1} were unknown. Therefore, dry matter, N, P, and K accumulation data collected in recent field experiments and projected using CERES-MAIZE (a physiologically-based growth model) were compared with benchmark data collected in 1940 and 1959. Rates of dry matter and nutrient accumulations were derived from compound cubic polynomial equations by using a mathematical procedure called splining. Resultant differentials were both continuous and smooth for the entire growing season. These analyses show that for corn a very critical period for nutrient and dry matter accumulation occurs approximately 50 days after planting. This time period coincides with growth stages V12 to V15 during which the potential ovule number and thus potential grain yield is being established. Dry matter and P accumulation rates at this growth stage were positively correlated (R^2=0.97) with final grain yield. The projected maximum rate of N accumulation required to achieve 18.6 Mg ha^{-1} (296 bu/a) was approximately 10 kg ha^{-1} day^{-1}. Accumulation of K was also positively correlated with grain yield (R^2=0.76), but when total seasonal K accumulation exceeded 300 kg ha^{-1} grain yield began to decline. This response may have been caused by a negative interaction between N and K. Overall, this review suggests that for high yield corn production, extending nutrient and dry matter accumulation

for more days by maintaining a minimum stress environment may be more important than achieving extremely high maximum rates of accumulation.

Additional Index Words: Nitrogen, phosphorus, potassium, *Zea mays* L.

INTRODUCTION

Numerous studies have been conducted to optimize nutrient, water, pest and other management factors which influence the mineral nutrition of corn (*Zea mays* L.) and thus determine crop production (Sayre, 1948; Nelson, 1956; Larson and Hanway, 1977). Two of those studies (Sayre, 1948; Hanway, 1962a,b) provide the most comprehensive description of corn growth, development, and macronutrient accumulation available in the literature. The importance of these studies can not be over emphasized because they provide the only data complete enough to calculate rates of dry matter and nutrient accumulation throughout the growing season. As such, they have become the benchmark for evaluating the effects of alternative management practices on seasonal uptake rates.

The maximum economic yield (MEY) concept is an alternative management system which seeks to create a minimum stress environment and thus exploit the genetic potential within each seed. This system integrates optimum levels of production inputs and follows with precision management throughout the growing season. As a result of MEY corn research, grain yields ranging from 15.7 to 21.2 Mg ha^{-1} have been achieved 20 times in only 5 years (Griffith and Dibb, 1985).

Improved hybrid potential, better water management, increased nutrient application, and significantly higher plant populations are among the factors which have contributed to the high yield levels associated with MEY and other current corn research. Recently, plant population has probably increased more than any other management factor. This occurred because after soil fertility, water, weed, and insect limitations to productivity are reduced, the arrangement and density of plants become the next most limiting factors (Downey, 1971). The world record 21.2 Mg ha^{-1} corn grain yield which was achieved at a population of 92,222 plants ha^{-1} (Armstrong et al., 1982) is one example in which high population and precision plant distribution have been used.

One effect of MEY changes in cultural practices has been to significantly increase total dry matter and nutrient accumulation when compared to measurements by Sayre (1948) or Hanway (1962a,b). Therefore, when rates of accumulation for current studies are projected from the benchmark experiments, values are often 4 to 5 times greater than those measured in the original studies (Welch and Flannery, 1985). The objective of this review was to evaluate the rates of dry matter and N, P, and K accumulations by corn producing various levels of grain yield and to compare those values with the benchmark values provided by Sayre (1948) and Hanway (1962a,b).

METHODS AND MATERIALS

Effects of changing cultural practices on corn growth and nutrient accumulation were evaluated by comparing data from Sayre (1948), Hanway (1962a,b), Rhoads and Stanley (1981), and Karlen and Camp (1982). To make the comparisons, similar data files were created on a Hewlett-Packard[3] (HP-87) microcomputer. Tabular data were available for all sources except Hanway (1962a,b). Those data, however, are a primary source for the most current corn growth, development, and nutrient publication (Ritchie and Hanway, 1984). Therefore, software was written to digitize total accumulation curves for plot 1004 (Hanway, 1962a,b). Digitization was accomplished using a flat-bed plotter and the HP-87 system.

Growth and N accumulation for an 18.6 Mg ha^{-1} (296 bu/a) corn grain yield were projected by using CERES-MAIZE (Jones, 1985), which is a physiologically-based growth and development model. The validity of those projections was assessed by comparing predicted and measured accumulation rates for corn grown in South Carolina during 1980 (Karlen and Camp, 1985).

Each data file was structured for input to one of two cubic spline programs. These mathematical procedures analytically described the nutrient and dry matter accumulation by fitting compound cubic polynomials to each curve. Rates of accumulation were then derived by differentiating the individual cubic polynomials which were fitted to each subrange of the independent variable (days after planting). At each junction between subranges, both the fitted curve and the derivative for these equations were continuous. Where sufficient data points existed, small irregularities were smoothed using a segmented statistical spline for which the abscissa was divided into typically three to five subranges (Kimball, 1976). For studies with few or widely-spaced points, a clamped cubic spline interpolant was used (Burden et al., 1981) with fixed derivatives (usually zero) at the endpoints. For this interpolant, a separate equation was generated between each pair of data points. For either method, data files containing the four coefficients of the cubic polynomial for each subrange of the segmented curve were written to a floppy disk.

Another program was written to plot either the accumulated amounts or rates of accumulation for each growing season. Plotting options included normalizing either axis and converting units among g plant^{-1}, kg ha^{-1}, and so forth. The conversion feature was essential because differences in plant population among the various studies complicated direct comparisons. For example, on a per plant basis, measurements by Sayre (1948) are greater but on a per hectare basis, measurements by Hanway (1962a,b) are greater. Therefore, when the amounts and rates of dry matter and nutrient accumulations were compared with the benchmark values, all data sets were plotted on an area basis.

RESULTS AND DISCUSSION

I. Splining to Evaluate Accumulation Rates

Seasonal dry matter, N, P, and K accumulation curves from Sayre (1948) and Hanway (1962a,b) are reproduced in Fig. 1 because those two data sets provide the current benchmark for evaluating nutrient and dry matter accumulation by corn. The relationship between actual or digitized points and the smooth curves calculated after the data files were mathematically splined is also shown. Good agreement between measured and calculated values was essential because rates of accumulation (Fig. 2) were determined by differentiating the equations that described each data set. We found that for files containing fewer than 7 observations per season, the clamped cubic spline interpolant (Burden et al., 1981) provided the more realistic derivative. However, for larger data sets, a segmented statistical spline (Kimball, 1976) provided a realistic, smoothed estimate of the dry matter or nutrient accumulation rate.

A comparison of traditional linear interpolation and the two splining techniques (cubic interpolant and smoothed statistical) using data from Sayre (1948) is shown in Fig. 3. For N and K, all three techniques were similar for this data set; however, as seen for dry matter and P, the least squares-smoothing technique can sometimes under-estimate peak rates of accumulation. The advantage of splining compared to the linear interpolant is that the derivative will be smooth and continuous even when there are few or irregularly spaced sampling points. Data from Sayre (1948) were collected every 3 days, and therefore, the linear interpolant is quite precise. However, sampling in more recent experiments is often much less frequent, and

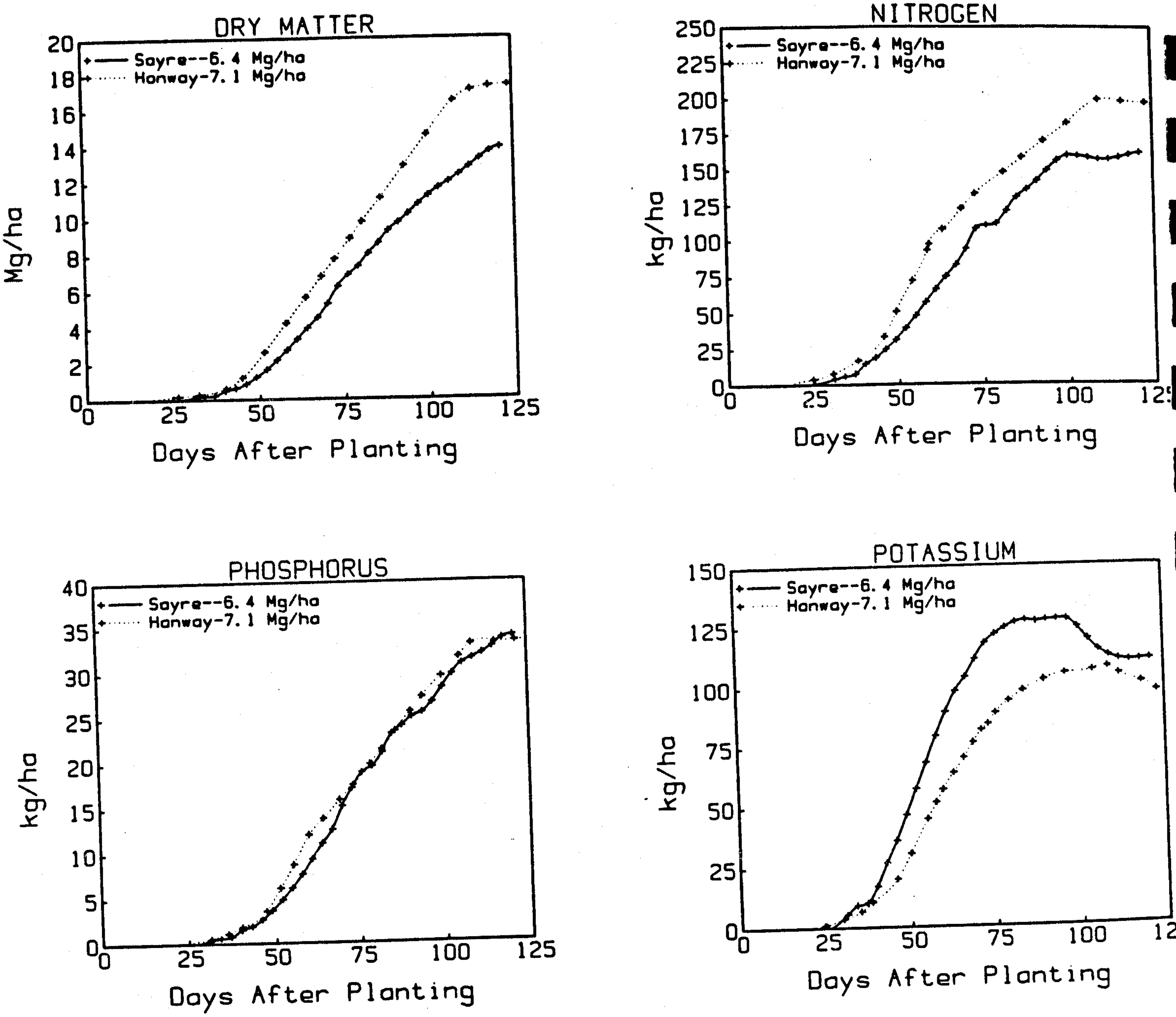

Fig. 1. Seasonal dry matter, N, P, and K accumulation for corn as measured by Sayre (1948) and Hanway (1962a,b).

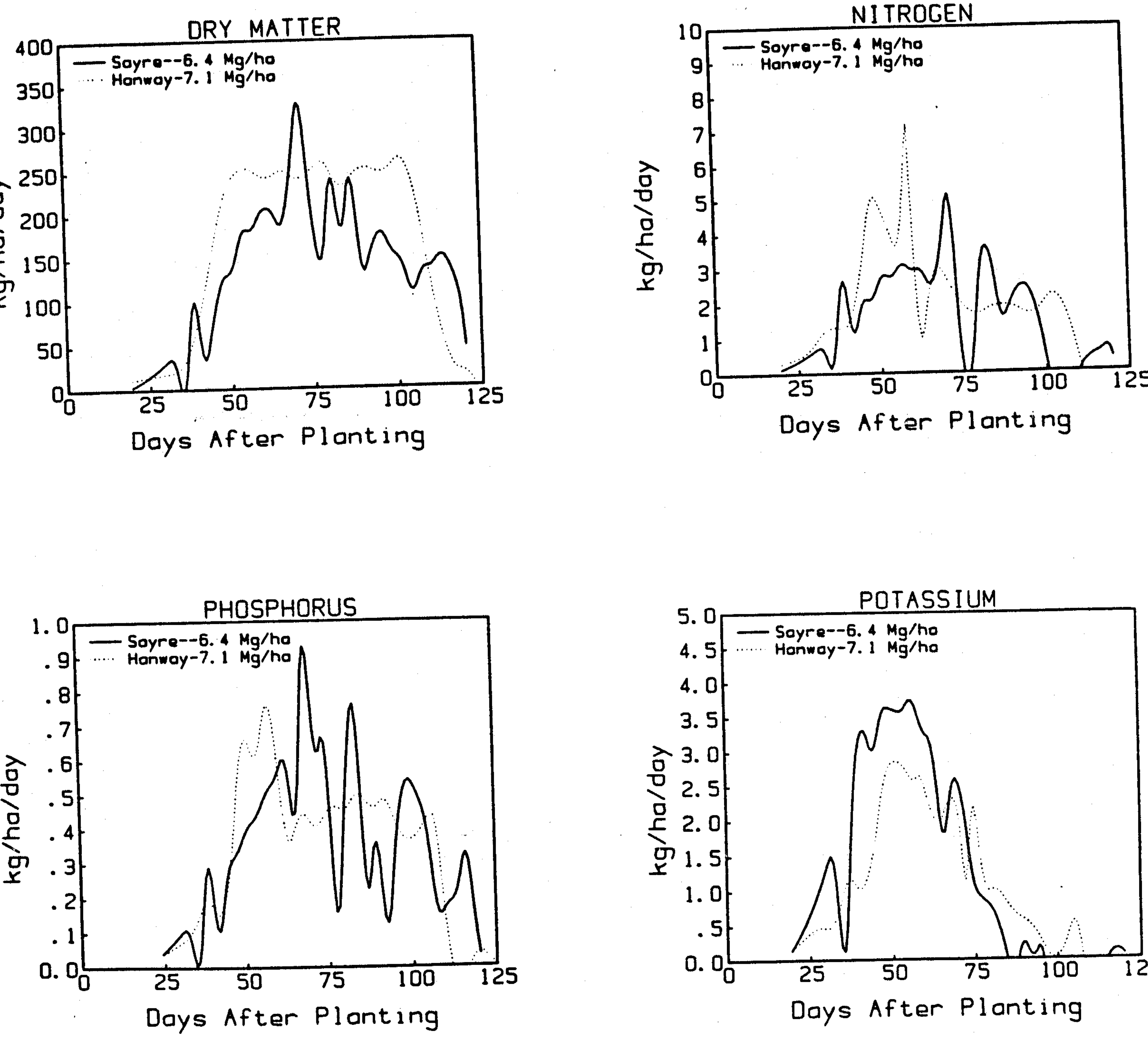

Fig. 2. Rates of dry matter, N, P, and K accumulation derived by splining data from Sayre (1948) and Hanway (1962a,b).

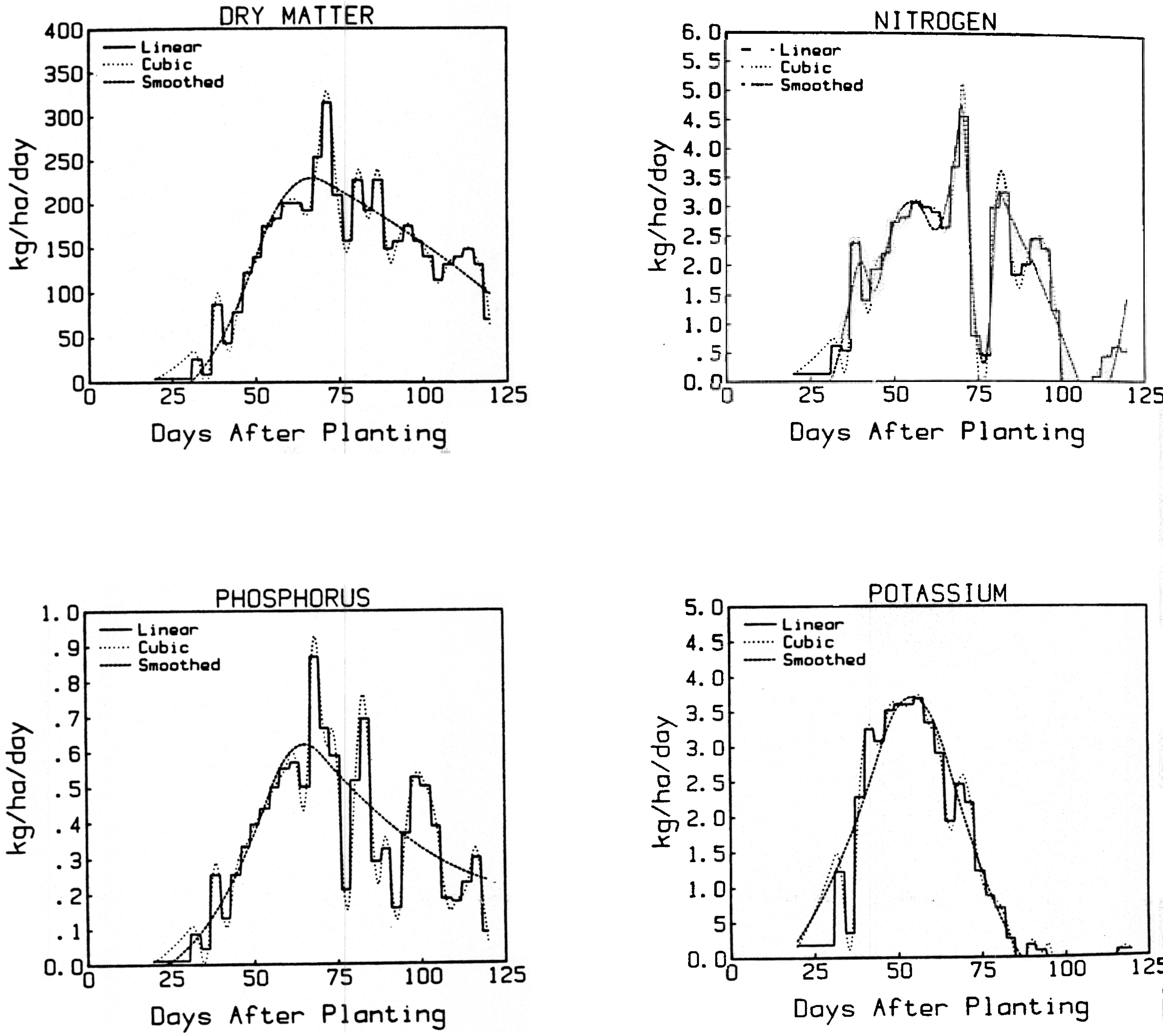

Fig. 3. Linear, cubic, and statistically smoothed interpolants of the Sayre (1948) growth and nutrient accumulation data.

therefore, splining made rate estimates appear more in line with cur-

uptake theory (Barber, 1984). Data in Table 1 show that published and derived accumulation rates for Sayre (1948) and Hanway (1962a,b) were in close agreement.

Table 1. Measured and fitted maximum rates of dry matter and nutrient accumulation using data from Sayre (1948) and Hanway (1962a,b).

Source	Parameter	Growth period days after planting	Measured	Fitted*
			------kg ha^{-1} day^{-1}------	
Sayre	Dry matter	64 to 76	243	225
Sayre	N	70 to 73	4.48	4.64
Sayre	P	64 to 76	0.66	0.59
Sayre	K	46 to 58	3.59	3.70
Hanway	Dry matter	45 to 109	250	260
Hanway	N	45 to 59	4.47	4.41
Hanway	P	45 to 59	0.55	0.60
Hanway	K	45 to 59	2.89	2.73

* Fitted values using a statistical cubic spline (Kimball, 1976)

Measured Yield by Nutrient Accumulation Relationships

Relationships between the amount and rate of dry matter, N, P, and K accumulations and grain yield for corn grown in Florida during

(Rhoads and Stanley, 1981) are shown in Figs. 4 and 5. The amount of fertilizer applied to the two treatments was equal (270 kg ha^{-1} of N, 80 kg ha^{-1} of P, and 225 kg ha^{-1} of K), but the frequency of application was either 6 or 12 times during the growing season. Grain yields for those two treatments averaged 7.96 or 9.66 Mg ha^{-1}

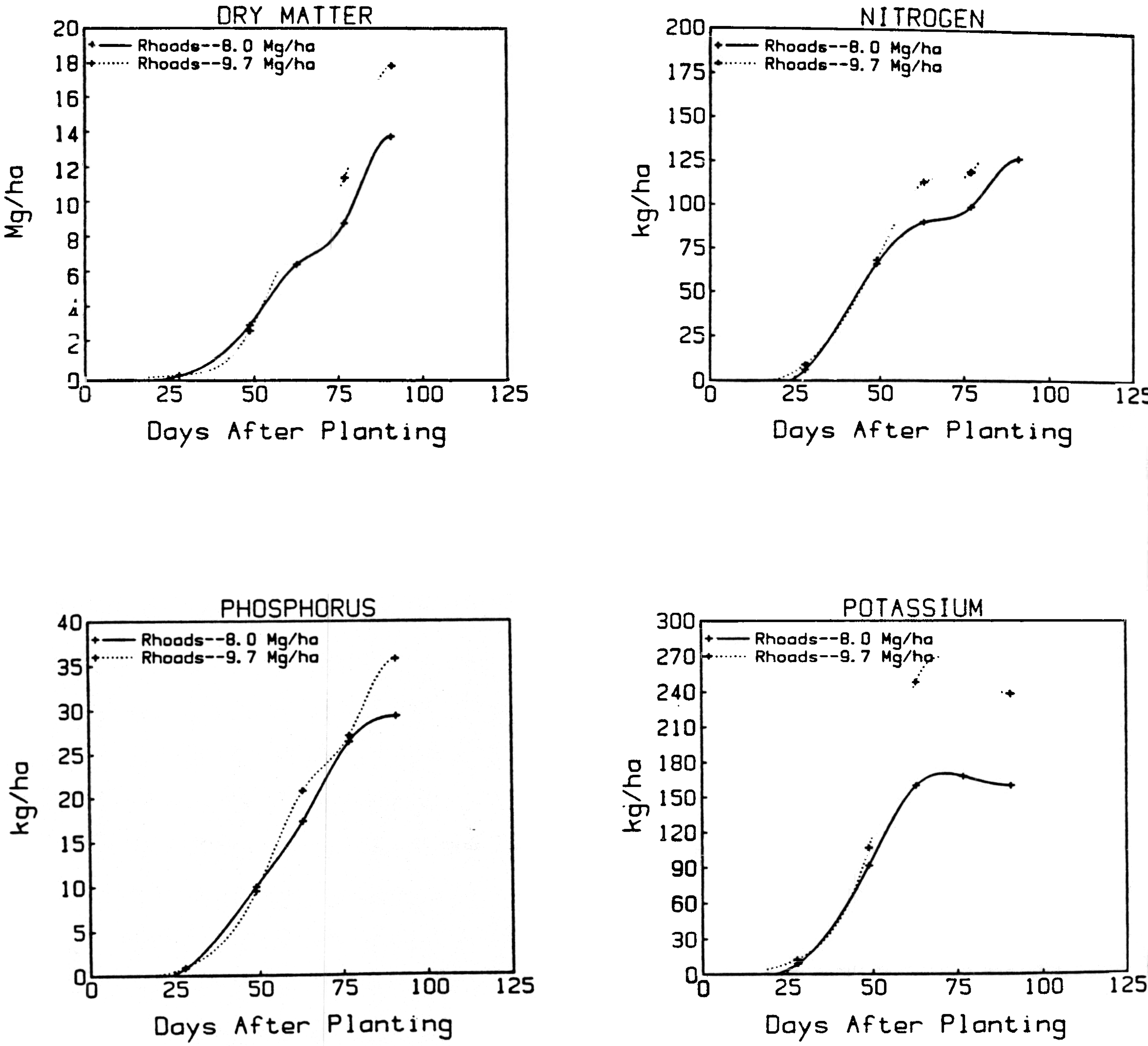

Fig. 4. Seasonal dry matter, N, P, and K accumulation measured by Rhoads and Stanley (1981) for corn at two yield levels.

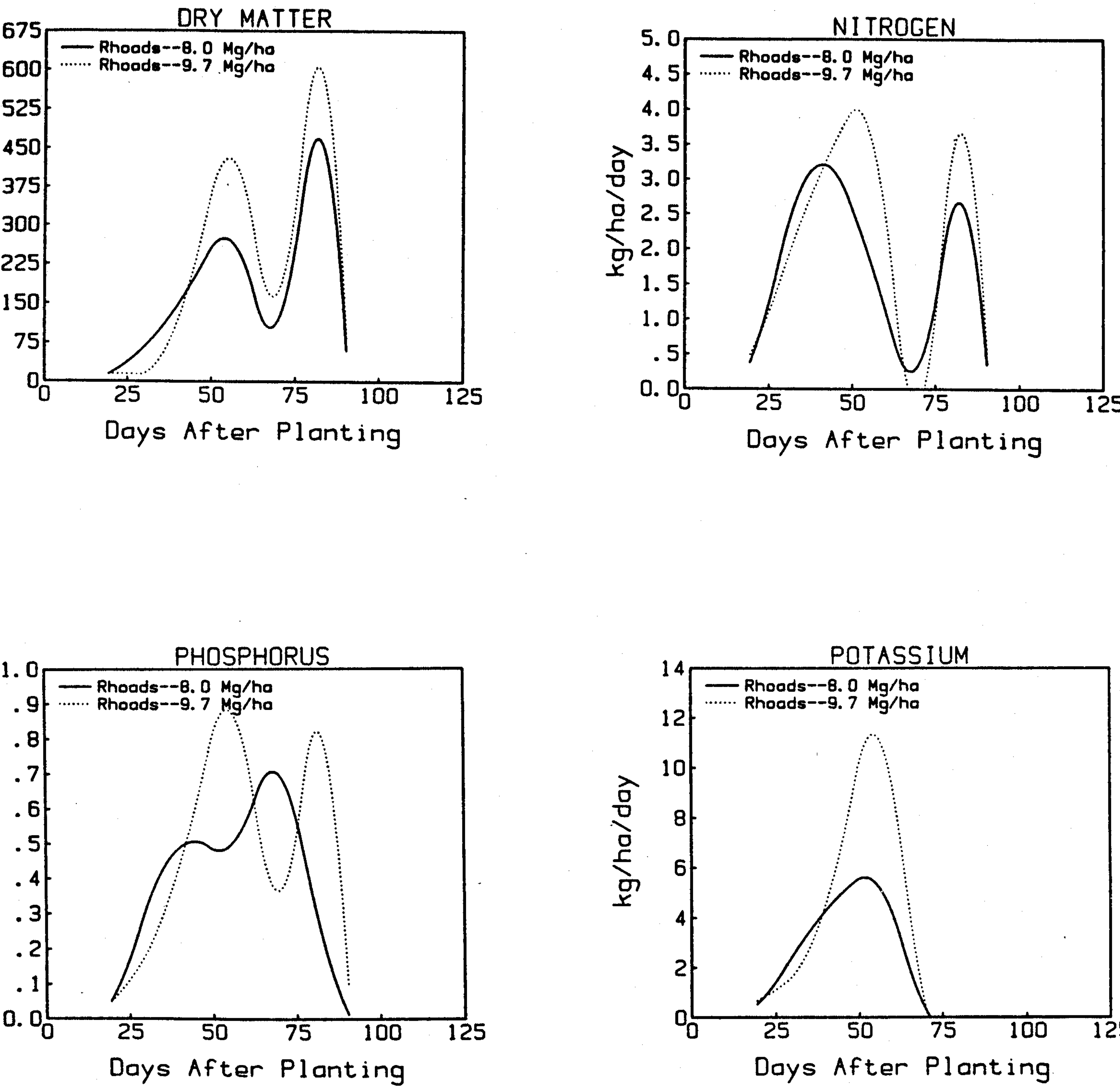

Fig. 5. Rates of dry matter, N, P, and K accumulation derived by splining data from Rhoads and Stanley (1981).

and were significantly different at the 10% level of probability. Early-season N concentrations were also significantly different, but this had very little effect on the total N uptake. The P concentrations were not significantly different, and grain yield was not correlated with total P uptake. However, total K uptake was significantly correlated with grain yield.

Rates of dry matter and nutrient accumulation (Fig. 5) indicate that final grain yield was most closely correlated with rates of accumulation about 50 days after planting. This time period probably coincided with growth stages V12 to V15 (Ritchie and Hanway, 1984) during which the potential number of ovules and thus ear size were being determined. Stress, especially during pollination, can reduce the number of kernels which develop, but potential grain yield is established during this very early growth period. This suggests that water, nutrient, weed, insect, light, or any other stress must be minimized at this early growth stage to achieve maximum grain yield. This will enable the plant to build a strong carbohydrate and nutrient reserve and thus establish a very high potential kernel number.

Seasonal dry matter and nutrient accumulation for corn, fertilized with an average of 264, 32, and 205 kg ha^{-1} N, P, and K, respectively, and grown at average populations of 7.0 or 10.0 plants m^{-2} (Karlen and Camp, 1985) are shown in Figs. 6 and 7. Grain yield declined each year for both population treatments. The exact cause for this is unknown, but dry matter and nutrient accumulation patterns indicate that there were some major seasonal differences. For the low

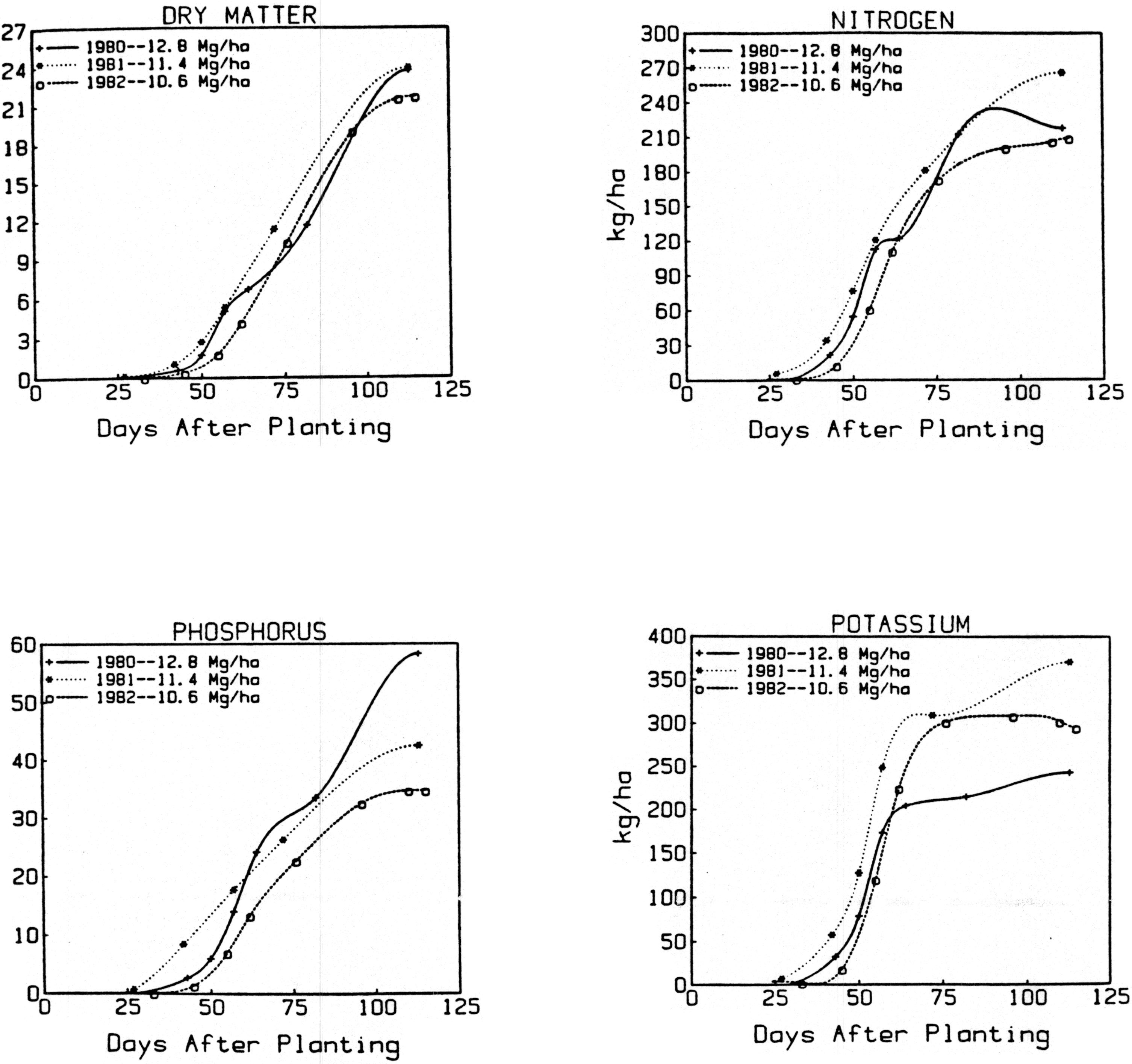

Fig. 6. Seasonal dry matter, N, P, and K accumulation measured in South Carolina for corn grown at an average "low" population of 7.0 plants m^{-2}.

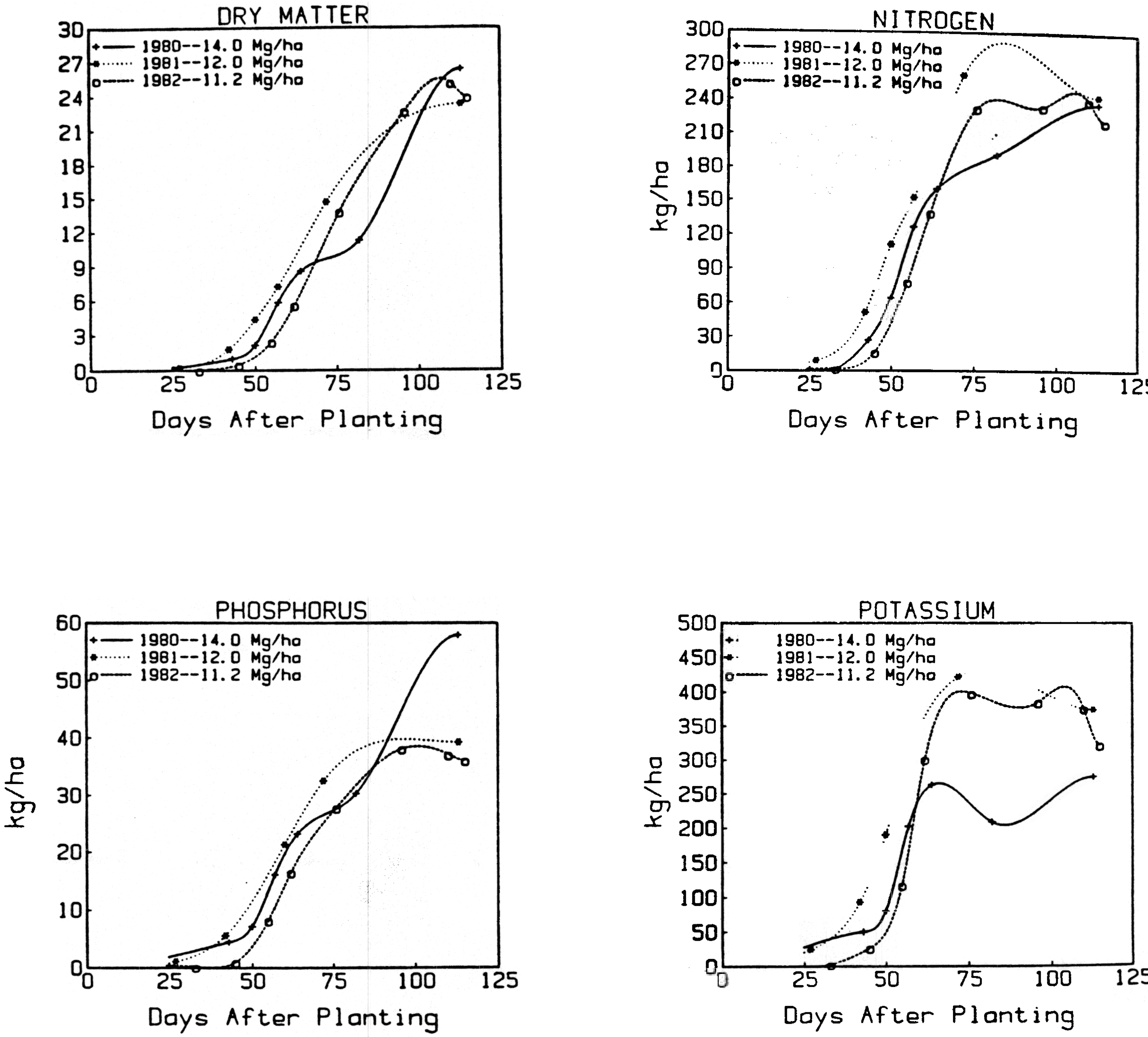

Fig. 7. Seasonal dry matter, N, P, and K accumulation measured in South Carolina for corn grown at an average "high" population of 10.1 plants m^{-2}.

population treatments (Fig. 6), total seasonal P accumulation was directly correlated with grain yield, but K accumulation was inversely correlated. Total N accumulation did not show a consistent relationship with grain yield, but the inverse relationship between grain yield and K accumulation may have been caused by an interaction between K and N (Nelson, 1956). Recently, Woodruff and Moore (1985) showed that on Coastal Plain soils high K depressed N and grain yield unless supplemental B was applied. In 1981 and 1982, B was applied prior to planting, and although leaf analyses indicated an adequate B concentration at silking (Karlen and Camp, 1985), the early-season K:B ratio may not have been at an optimum level. For the high population treatments (Fig. 7), total dry matter, N, and P accumulations were also greatest and K lowest in 1980 when grain yield averaged 14.0 Mg ha^{-1} However, in 1981 and 1982 when total K accumulation was much greater than in 1980, N and P accumulations as well as grain yield were much lower.

Rates of dry matter and nutrient accumulation for the two population treatments in 1980, 1981, and 1982 are shown in Figs. 8 and 9. In 1980, when grain yields for the low and high population treatments averaged 12.8 and 14.0 Mg ha^{-1} respectively. These data also showed peak rates of dry matter and P accumulation approximately 50 days after planting. In 1981 and 1982, these early-season peaks were lower and less distinct than in 1980, and grain yields in those two years were lower. Water was not a limiting factor in any year because supplemental irrigation was applied at about this time. Calculated water

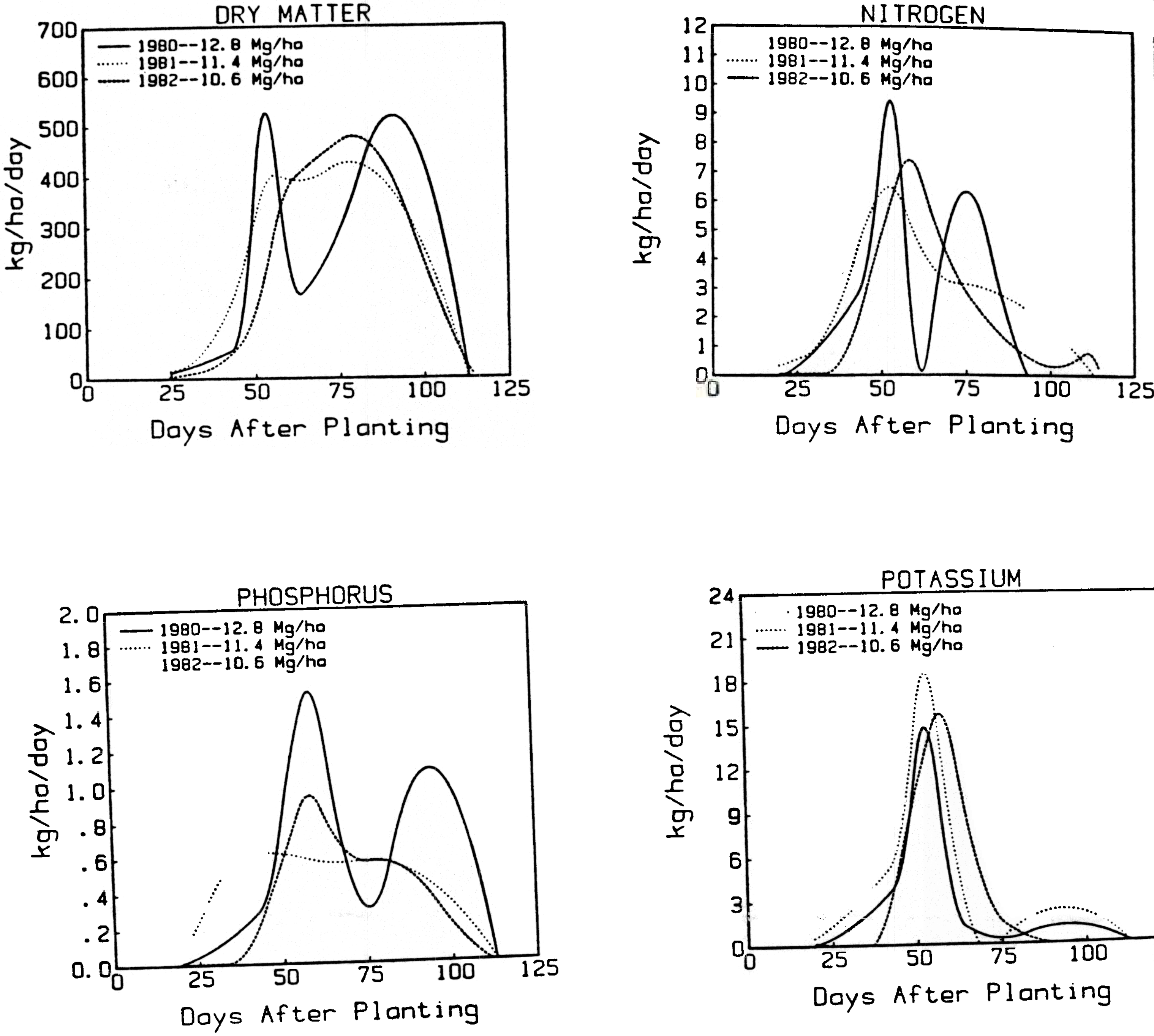

Fig. 8. Rates of dry matter, N, P, and K accumulation derived by splining low population uptake data for corn grown by Karlen and Camp (1985) in South Carolina.

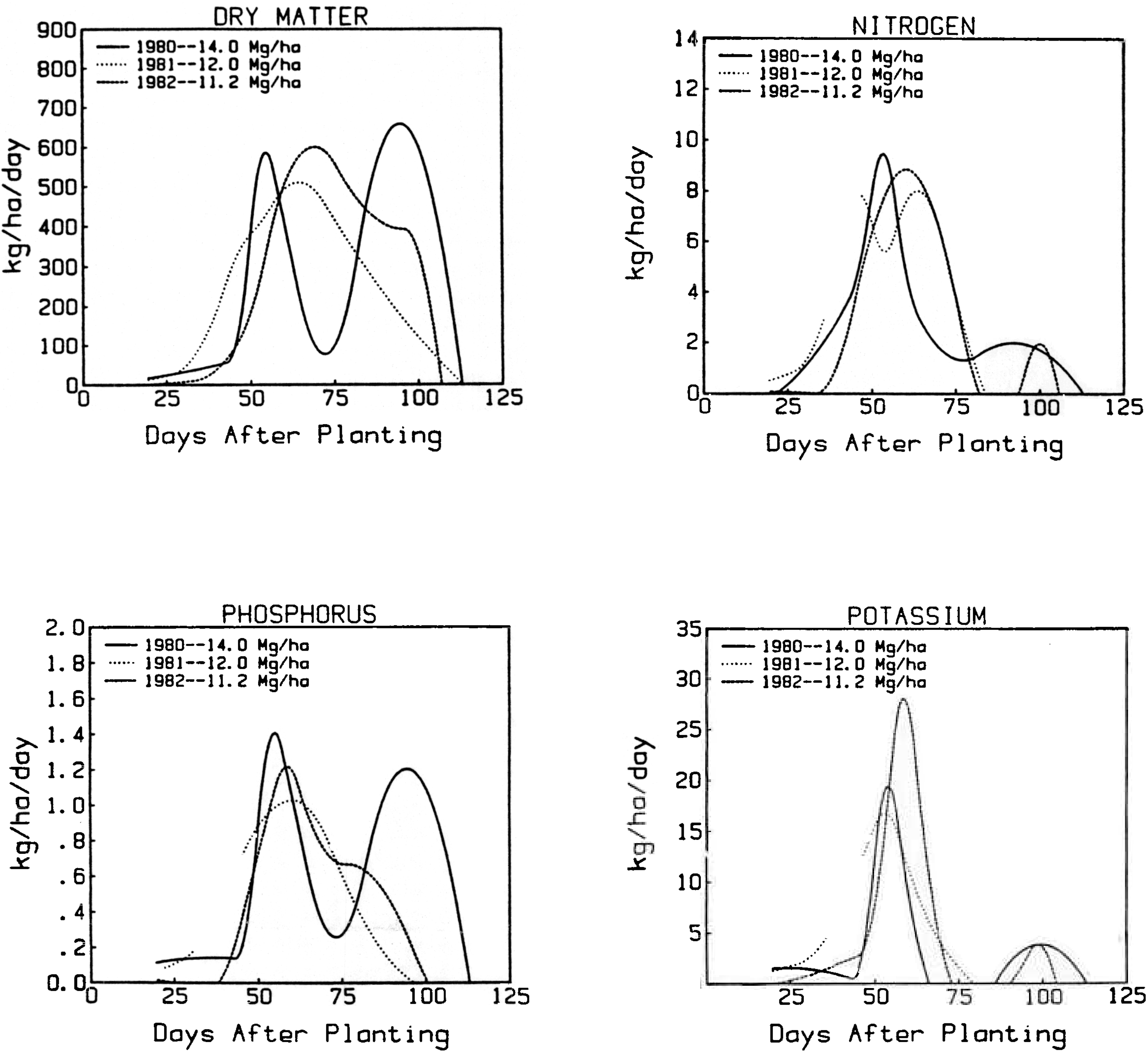

Fig. 9. Rates of dry matter, N, P, and K accumulation derived by splining high population uptake data for corn grown by Karlen and Camp (1985) in South Carolina.

balances showed that the water content in the root zone was greater than 50% of available water content during this period each year. There was no significant difference in grain yield for the high and low fertilizer treatments (Karlen and Camp, 1985) suggesting that the lower yields in 1981 and 1982 were not caused by simple nutrient deficienies. The most plausible explanation appears to be an imbalance between N and K which also resulted in substantially less P accumulation. Further research is necessary to resolve this. However, the relationship does support our previous observations that during the late vegetative growth stages, when the yield potential is being established, growth conditions must be optimized to ensure maximum grain yields.

In Figs. 10 and 11, the amount and rate of corn dry matter and nutrient accumulation measured by Rhoads and Stanley (1981) in 1978 and by Karlen and Camp (1985) in 1980 are compared with measurements by Sayre (1948) and Hanway (1962a,b) to evaluate the effects of hybrid improvement, increased fertilization, and increased plant population. These data show that as grain yields have increased, seasonal accumulation of dry matter and nutrients have also increased. Linear regression analyses for grain yield vs dry matter, N, P, or K accumulation gave R^2 values of 0.93, 0.51, 0.88, or 0.76, respectively, showing that for these four data sets, total dry matter and P accumulations were most highly correlated with final grain yield. The lower R^2 value for N probably occurred because the high rainfall period 63 to 77 days after planting appeared to reduce total N accumulation in

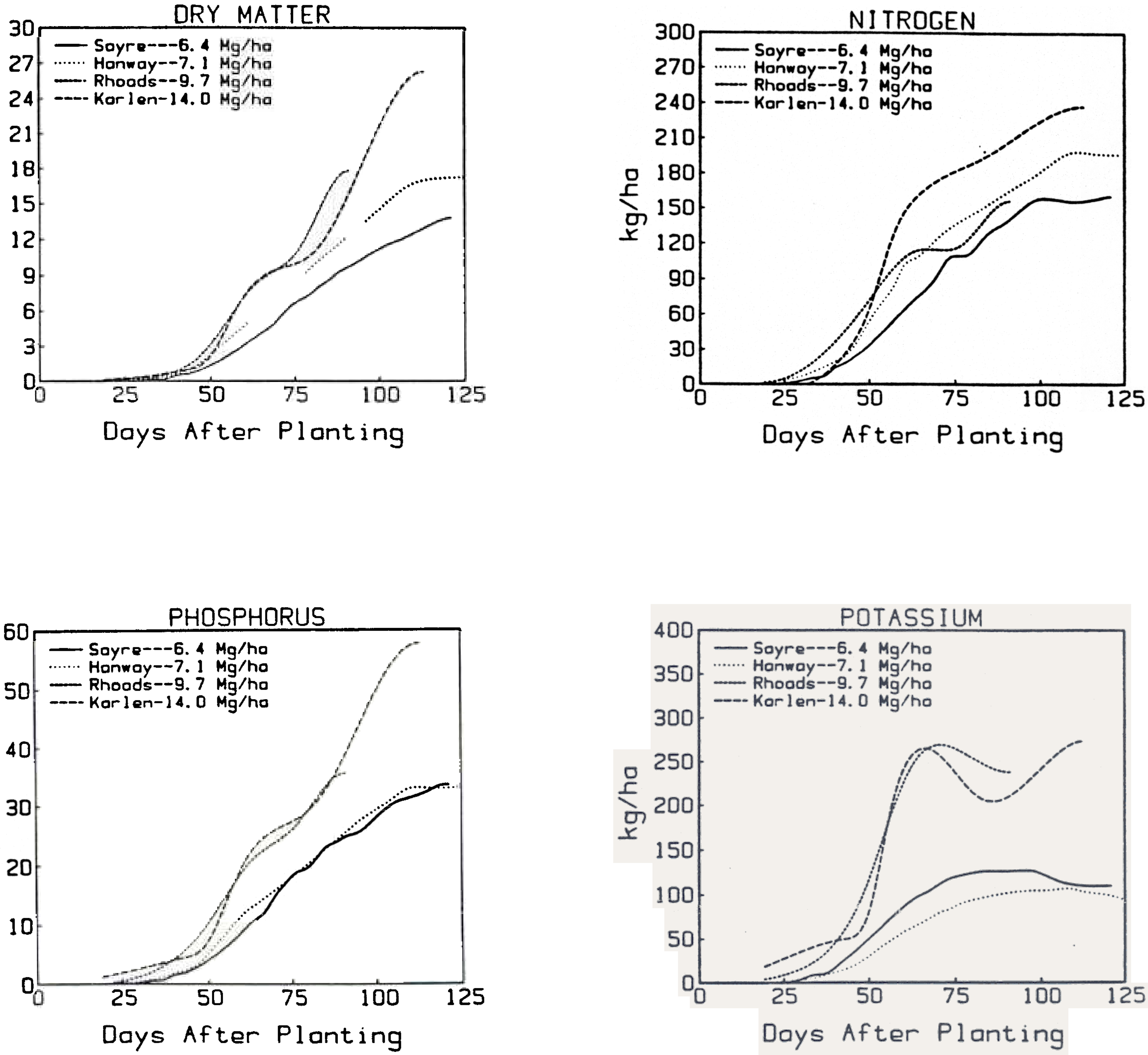

Fig. 10. Seasonal dry matter, N, P, and K accumulation measured for different corn grain yield levels by Sayre (1948), Hanway (1962a,b), Rhoads and Stanley (1981), and Karlen and Camp (1985).

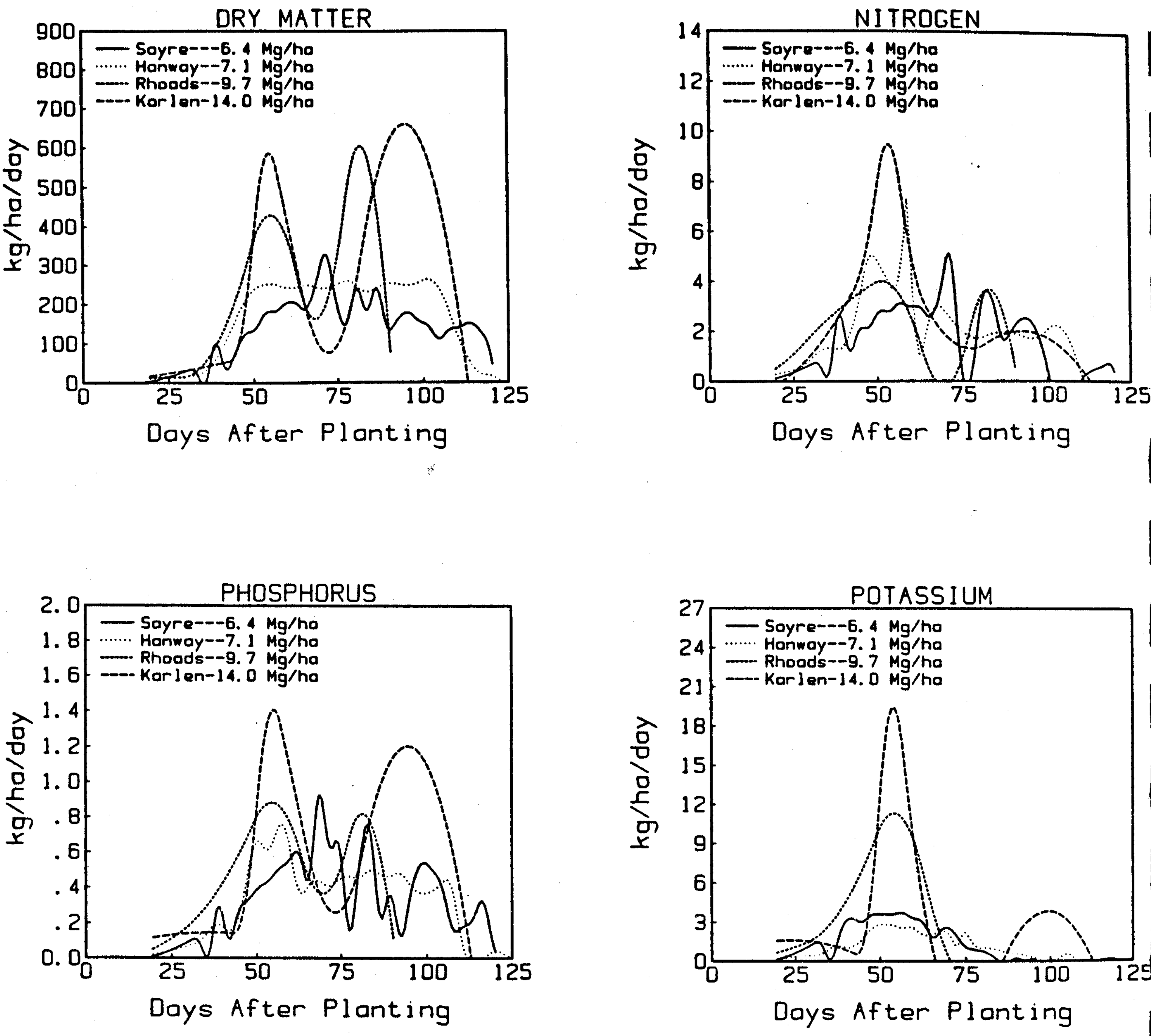

Fig. 11. Rates of dry matter, N, P, and K accumulation derived by splining accumulation data measured by Sayre (1948), Hanway (1962a,b), Rhoads and Stanley (1981) and Karlen and Camp (1985).

the study by Rhoads and Stanley (1981). Reduced N accumulation during this period coupled with a shorter growing season resulted in less N accumulation than for the study by Hanway (1962b) although grain yield was greater. The low R^2 for K probably reflected the relatively low amount of K accumulation measured by Hanway (1962b) for plot 1004.

The best predictors of final grain yield (R^2=0.97) were dry matter rates or P accumulation about 50 days after planting. When planning for maximum economic yields, this early-season growth stage appears to be much more sensitive to stress than previously reported (Larson and Hanway, 1977). Another notable difference among these four data sets is the rate and length of dry matter accumulation during grainfill. This is most distinct when comparing the data from Rhoads and Stanley (1981) and Karlen and Camp (1985), although the hybrid used by Hanway (1962a) also accumulated more total dry matter than the one reported by Sayre (1948). Maintaining a minimum stress environment will be essential for achieving maximum economic yields. Any stress factor such as drought, weeds, or insects can cause the grainfill period to be shorter and thus decrease grain yields. To prevent a shortened grainfill period in the more southern regions, the plant genetic material must also be able to withstand the high temperatures and rapid accumulation of heat units associated with the summer months

The amount and rate of K accumulation was also much greater in studies by Rhoads and Stanley (1978) and Karlen and Camp (1985) than in those by Sayre (1948) or Hanway (1962b). Peak rates of accumulation were approximately 12 or 19 kg ha^{-1} day^{-1} in the more recent studies as compared to approximately 2.5 or 3.5 kg ha^{-1} day^{-1} in the benchmark studies. Calculated peak rates of K accumulation in these studies are even greater than those projected by Welch and Flanery (1985) from total K accumulation for high yield studies in New Jersey and Illinois. This difference probably occurred because projections by Welch and Flannery (1985) were made using the linear estimate of 38% of total accumulation as the peak rate of accumulation rather than the continuous differential made possible by using the splining technique. Both techniques, however, indicate that current corn hybrids grown at high population have much higher rates of K accumulation than those used to establish the benchmark. This probably reflects both the higher plant population and the associated need for more K to ensure adequate stalk strength in current hybrids. However, these high rates of K accumulation may have a detrimental effect if they interfere with N accumulation (Nelson, 1956; Woodruff and Moore, 1985).

III. Projected Dry Matter and N Accumulation

Seasonal dry matter and nutrient accumulation data associated with high (>16 Mg ha^{-1}) corn grain yield were not found in either a published or unpublished form. Therefore, a physiologically-based growth model (Jones, 1985) for corn (CERES-MAIZE) was used to estimate the seasonal rates of dry matter and N accumulation required to achieve 18 Mg ha^{-1} grain yields. To make those projections, seasonal weather and management information associated with the 14.0 Mg ha^{-1} yields for 1980 (Karlen and Camp, 1985) were used as initial input parameters. These inputs included soil characteristics, hybrid characteristics, planting date, amounts and dates of N fertilization, seasonal rainfall plus irrigation, maximum and minimum temperature, and daily solar radiation.

The model estimates of grain yield, dry matter, and N accumulation were compared to the measured data for 1980 to evaluate the accuracy of this approach. Data in Fig. 12 show that projected total dry matter and N accumulation as well as grain yield were very close to the measured amounts. The projected rates of accumulation also had similar seasonal patterns. This indicated that although there were small absolute differences between the mesured and predicted values, using CERES-MAIZE was a valid approach for projecting the dry matter and N accumulation rates required for high yield corn.

To force the model to produce higher grain yields, input parameters were changed from those actually used or measured. The model did not project any water stress at the measured or high yield level, so there was no increase in water applications. There was a slight predicted N stress for the measured 14.0 Mg ha^{-1} yield when 260 kg ha^{-1} of N was applied. Therefore, to achieve an 18.6 Mg ha^{-1} yield, the N rate was increased to 390 kg ha^{-1}. The remaining parameters which could be modified included soil characteristics, hybrid traits, or daily weather measurements.

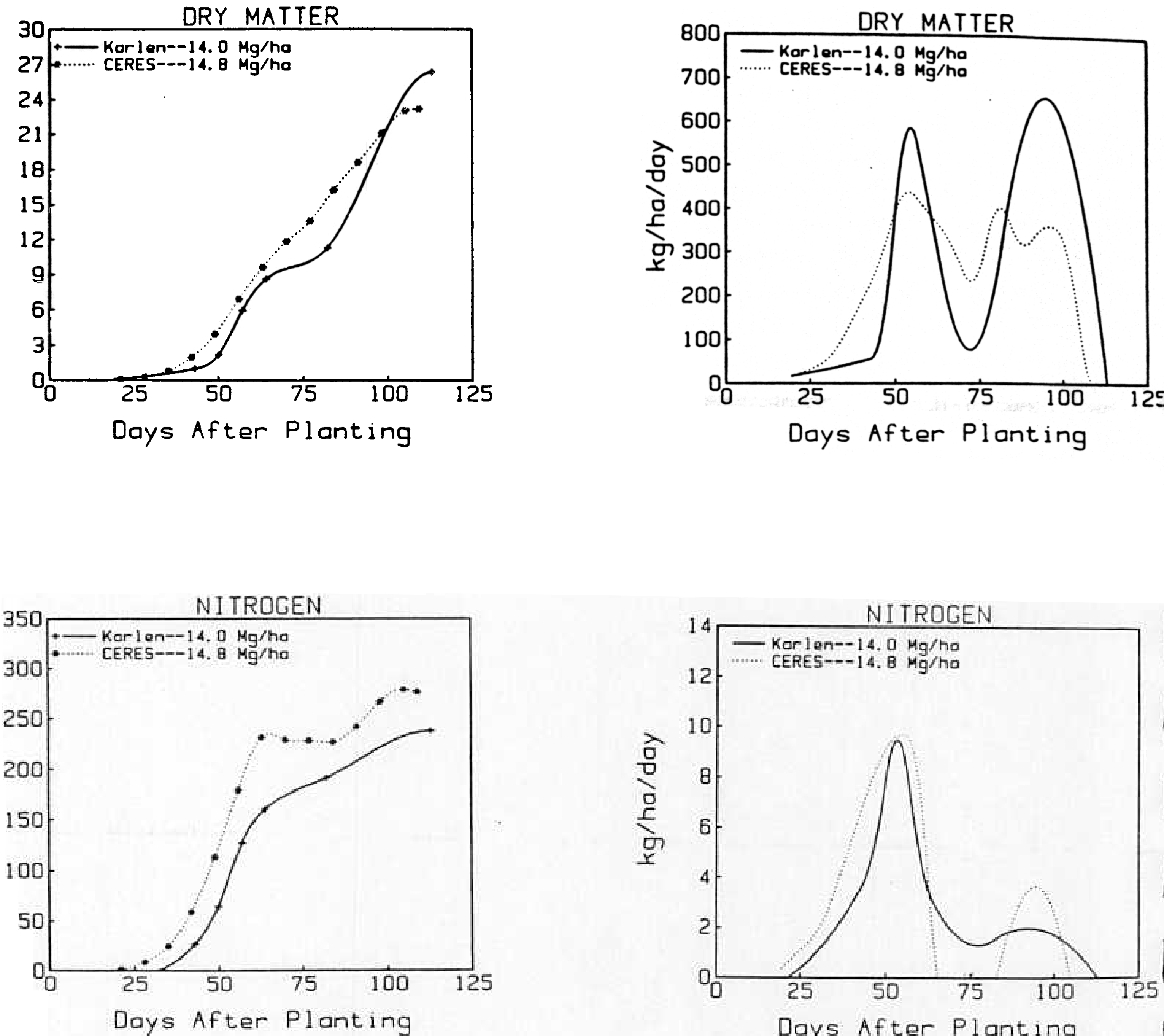

Fig. 12. Measured and CERES-MAIZE projected amount and rate of dry matter and N accumulation for high-yielding corn grown in South Carolina in 1980.

The soil characteristics were not changed so that the projections would be realistic for a Norfolk (fine-loamy, siliceous, thermic Typic Paleudult). Some "creative" plant breeding was done to allow longer vegetative and grainfill periods than we had measured for Pioneer Brand 3382. These changes gave the dry matter rate curve (Fig. 13) a shape similar to that measured by Hanway (Fig. 2), although for the 18.6 Mg ha^{-1} yield, dry matter accumulation was approximately 125 kg ha^{-1} day^{-1} greater than for the 7.1 Mg ha^{-1} yield measured by Hanway (1962a). The peak rate of N accumulation required to produce 18.6 Mg ha^{-1} was approximately 9.5 kg ha^{-1} day^{-1} which was not substantially different (Fig. 13) from the rate required to produce the measured 14.0 Mg ha^{-1} yield. However, the length of time for which the peak rate was maintained was much greater. The growth period for which the peak rate of N accumulation of projected was once again centered around 50 days after planting. There was a second period of rapid N accumulation during grainfill, but this peak was only about 7 ka ha^{-1} day^{-1} and was much shorter in duration than the peak during the vegetative growth stages.

A second and more drastic approach used to increase yield was to increase both the length of grainfill and the amount of solar radiation received during the entire growing season. Solar radiation was increased by approximately 25% (from 2.3 to 2.9 GJ m^{-2} or 55,000 to 70,000 ly). Using additional light to force the model to produce higher corn yields is quite interesting, since that is one rationale for the precision planting in MEY studies. Also, light is one factor

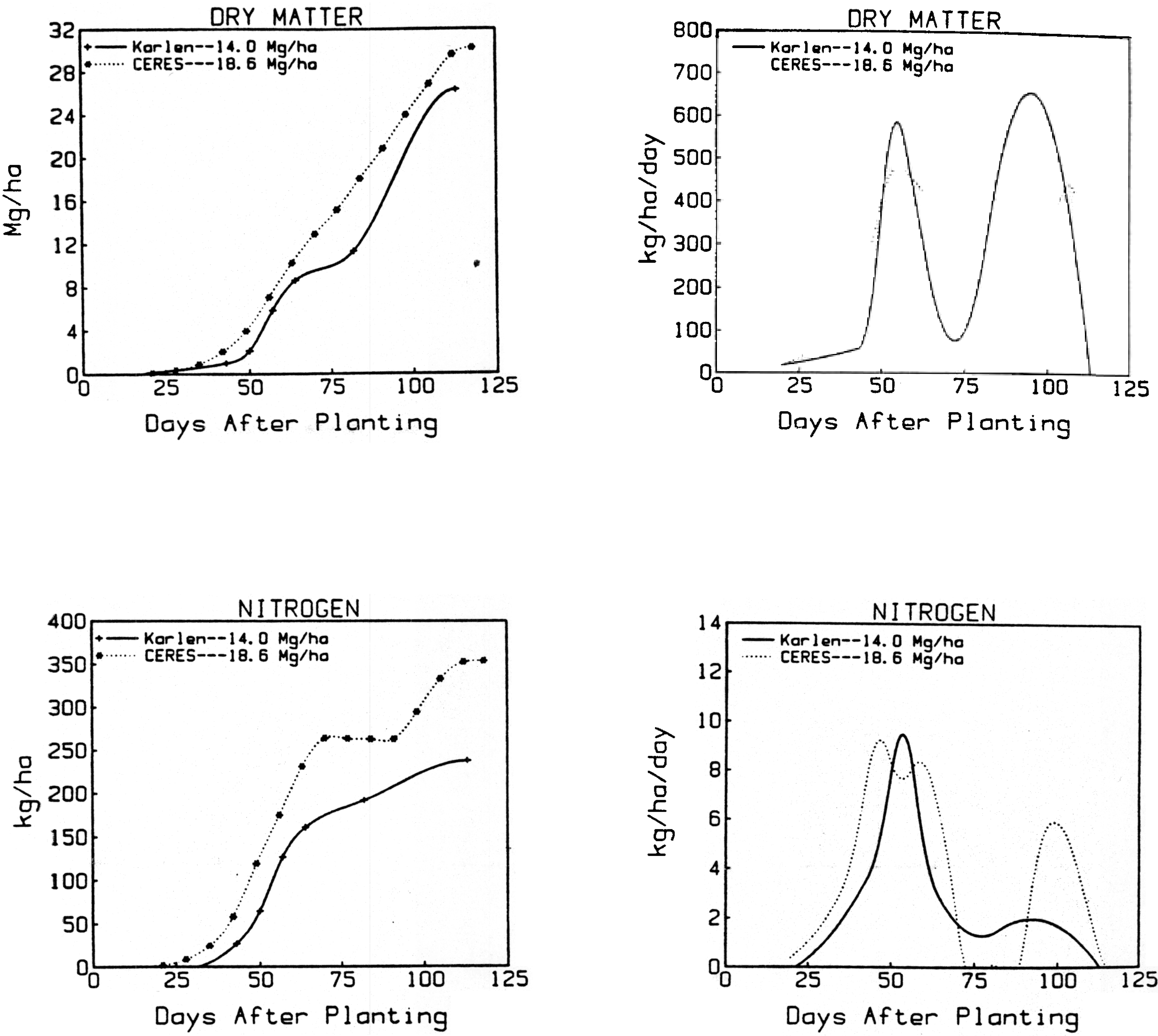

Fig. 13. Amount and rate of dry matter and N accumulation projected for corn using CERES-MAIZE with longer vegetative and grainfill growth stages.

being studied in current MEY studies in Illinois (Welch and Ottman, 1983). A projected grain yield of 18.5 Mg ha^{-1} was achieved using this techique (Fig. 14). The predominant changes which occurred by increasing solar radiation and the length of grainfill were an increased amount and rate of dry matter and N accumulation early in the growing season.

Both techniques for projecting high corn yield using CERES-MAIZE predicted major changes before the crop began to tassel, pollinte, or initiate grainfill. This observation substantiates that for maximum corn yield, dry matter and nutrient uptake must be near peak levels during growth stages V12 to V15 when the potential number of kernels and thus potential ear size are being determined. Several management factors can reduce yield after the potential kernel number is established, but apparently nothing can increase it.

SUMMARY AND CONCLUSIONS

Past, present, and projected amounts and rates of dry matter, N, P, and K accumulation are reviewed. Splining is used as a new technique for projecting a continuous and smooth differential throughout the growing season. This technique can be used to identify more closely the growth stage at which major changes in the rate of accumulation occur.

To achieve maximum corn grain yield, a very critical period for nutrient and dry matter accumulation appears to occur about 50 days after planting or when plants are establishing their maximum yield

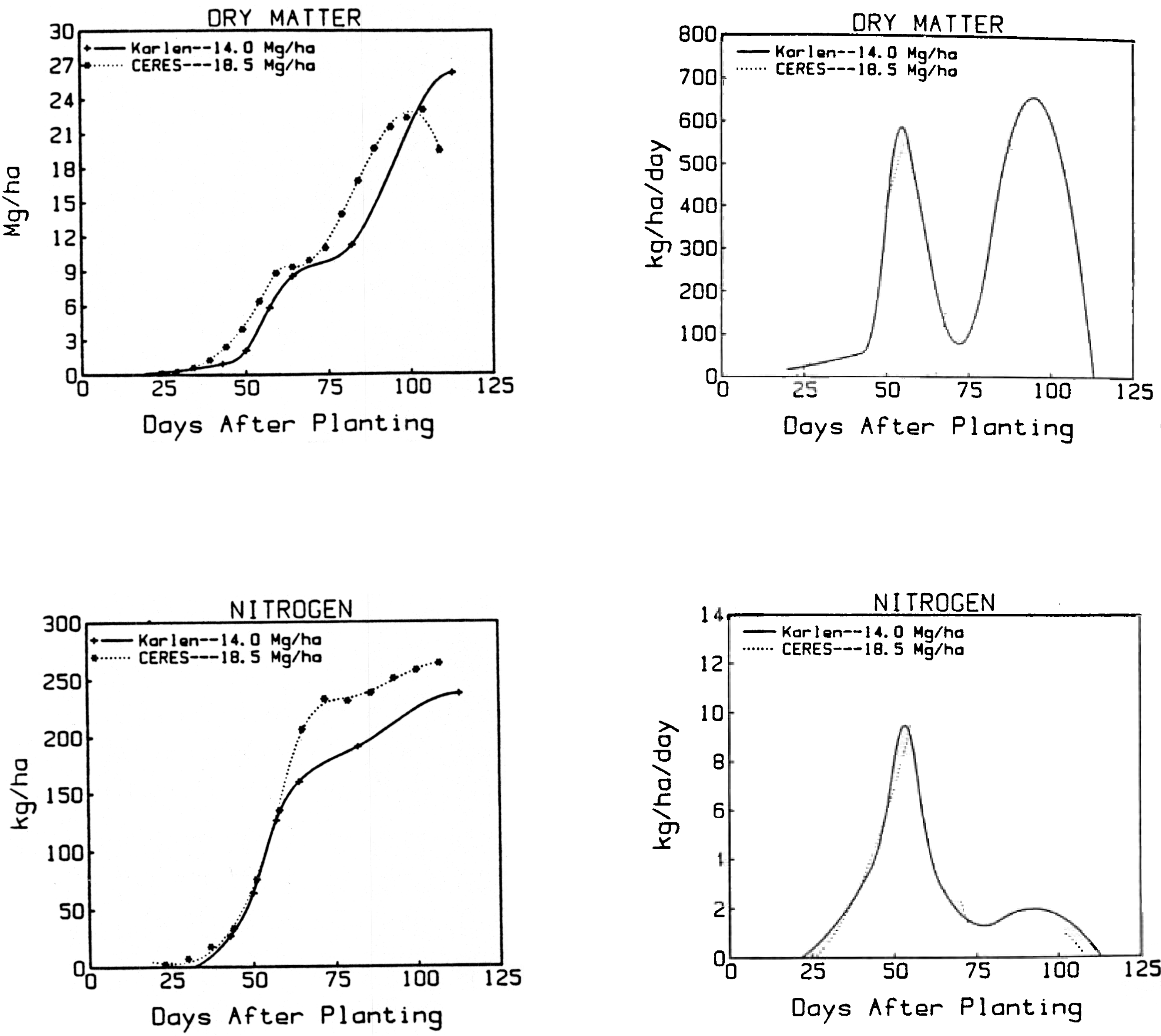

Fig. 14. Amount and rate of dry matter and N accumulation projected for an 18.5 Mg ha^{-1} corn grain by using CERES-MAIZE with increased solar radiation and a longer grainfill period.

potential for the season. This, according to current nomenclature, would coincide with growth stages V12 to V15. The length of grain-fill was identified as an especially important period in the Southeast by comparing yields obtained in Florida and South Carolina. This presumably occurs because thermal units accumulate very rapidly as the growing season progresses in this region.

The projected maximum rate of N accumulation required to achieve 18.6 Mg ha^{-1} (296 bu/A) corn appears to be about 10 kg ha^{-1} day^{-1} Peak rates of P accumulation appear to appear to coincide with peak rates of dry matter accumulation during both the vegetative and reproductive growth stages. For K, peak rates of nearly 20 kg ha^{-1} day^{-1} were observed when grain yields of 14.0 Mg ha^{-1} were measured, but when seasonal K accumulation exceeded 300 kg ha^{-1} in 1981 and 1982, grain yield and N accumulation declined. This suggests that a negative N and K interaction may have occurred in these studies and that this interaction should be investigated for corn in future maximum economic yield experiments.

ACKNOWLEDGEMENT

The authors would like to thank Dr. C. A. Jones and Ms. Diane Badgley for their assistance in making the CERES-MAIZE evaluations and projections.

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